AN APPRAISAL ON ASSESSMENT OF HAZ TOUGHNESS

A. SESHU KUMAR*, B. RAVI KUMAR*, G. L. DATTA and V. R. RANGANATH****

*National Metallurgical Laboratory, Jamshedpur 831 007,
**Indian Institute of Technology, Kharagpur 721 302

(Presented at the International Welding Conference (IWC-2001) on Advances in Welding & Cutting Technology held on 15th–17th February, 2001 at New Delhi.)

ABSTRACT

Advances in welding technology and materials science have resulted in great improvements in the reliability of welded structures. However, catastrophic failures have not been uncommon. Most of the weld related failures have been attributed to have originated from the heat affected zone (HAZ), which is believed to be the weakest link in the heterogeneous welded joint comprising of weld metal, HAZ and the unaffected base material. One of the key requirements in the integrity assessment of welded joints is the availability of representative property data for the HAZ, which can be used for comparing with the applied stress and predict critical stress or the remaining life. The difficulties in estimating the properties of the HAZ are compounded by a microstructural gradient within a narrow zone. In this investigation, detailed experimental studies were carried out on the HAZ obtained in manual metal arc, submerged arc and gas metal arc welding processes. The properties evaluated include hardness, tensile data, CVN impact and fracture toughness. Inspite of placing the notch close to the fusion boundary, CVN impact tests do not provide the correct estimation of toughness because of irregular HAZ boundary and the finite root radius of the CVN notch (0.25mm) which entails the crack to sample several heterogeneous grains. On the other hand, a sharp fatigue precrack narrows down the microstructural heterogeneity in the fracture toughness tests. Even so, the variation of the fracture toughness (CTOD) within the HAZ is as unpredictable as in CVN toughness. This depends on the crack tip encountering either a local brittle microstructure indicating pop-ins or the deviation of crack tip into adjacent softer microstructural regions resulting in an apparent increase of fracture toughness. Literature is lacking in proper validation criteria before the HAZ toughness test results can be applied for integrity assessment. The present paper systematically investigates the problems associated with evaluation of the properties of HAZ in typical C-Mn-Nb micro alloyed steel.

Key Words : HAZ, microstructural gradient, tensile data, impact toughness, fracture toughness, CTOD, pop-ins, C-Mn-Nb micro alloyed steel.

INTRODUCTION

For the assessment of design against ductile failure, the properties such as tensile, impact and bend ductility are assessed through weld composite specimens by conventional standards [1, 2]. The mechanical properties of the composite joint assessed in terms of standard tensile, bend or impact tests are insensitive to local alterations in the properties as envisaged in the HAZ. On the other hand, in fracture mechanics tests the crack tip environment, encompassing the local variations in the microstructure, is taken into account to provide a representative value of the materials resistance to crack growth while evaluating HAZ toughness. The present day practices [3 - 5] suggest the application of FM based concepts, such as, crack tip opening displacement (CTOD), dc, for the assessment of integrity/ compare the criticality of flaws in welded joints, especially in critical applications. British Standards Institution published a document [3] based on CTOD design curves to streamline the fracture assessments of fusion welded structures with a specific reference to the evaluation of HAZ. The reliability of the assessment of welded joints greatly depends on the accuracy of mechanical and fracture property data of HAZ generated from the laboratory experiments.

In the present investigation, detailed experimental studies were carried out on the HAZ obtained in manual metal arc (MMA), submerged arc (SA) and gas metal arc (GMA) welding processes. The properties evaluated include hardness, tensile data, CVN impact and fracture toughness which were discussed in terms of HAZ microstructures obtained in a typical C-Mn-Nb micro alloyed steel.

EXPERIMENTAL PROCEDURE

Typical niobium micro alloyed steel in the form of 12mm thick plate in the hot rolled and normalised condition was used in the present investigation. The chemical composition and the conventional mechanical properties of the steel (Table I) indicate that the steel conforms to ASTM A633 Gr.C specifications. The microstructure of the base material in the as received condition, shown in Fig. 1, typically displays uniformly distributed ferrite pearlite microstructure. The average ferrite grain size is of the order of 15-17mm, while the prior austenite grain size is around 42mm.

The test specimens for various mechanical tests were machined from full thickness multi-pass welded plates obtained by employing MMA, SA and GMA welding processes. The details of weld edge design and

Table I : Chemical composition and mechanical properties of the base steel.

i) Chemical analysis (wt.%)

C	Mn	Si	S	P	Nb	N_2	O_2	Carbon equivalent, CE_{IIW}
0.19	1.48	0.032	0.025	0.033	0.012	0.0087	0.0085	0.43 0.26

ii) Mechanical properties

Yield stress, MPa	Tensile stress, MPa	Elongation, %	CVN impact toughness, J	CTOD,δc,mm
400 (min.)		22 (min.)	84	0.188

the weld parameters are reported in [6]. An attempt was made to quantify the phases present in the weld HAZ conditions. For this a minimum of 10 fields were scanned across the specimen area manually using an optical microscope and the volume fraction of the phases were estimated using point counting technique. The results of the quantitative microstructural analysis are reported in Table II.

Round tensile specimens of 6mm diameter and 30mm gauge length were machined from welded plates and care was taken to keep the straighter HAZ region of the half K type weld joint in the middle of the gauge length of the specimen. Tensile tests were conducted, as per ASTM standard E-8M, under displacement control at a rate of 0.2mm/min. Elongation was measured by an extensometer of 25mm gauge length. Impact tests were conducted on standard charpy specimens at room temperature

Fig.1 : Microstructure of the steel in the as received condition (nital etch, 500x)

Table II : Quantitative microstructural analysis of CGHAZ (vol.%).

Phase constituent	MMAW	SAW	GMAW
Grain boundary ferrite	2	4.5	1
Ferrite side plates	2	4.0	8
Intragranular constituent	95	91.5	36
Martensite	1	not detected	55

according to ASTM E 23. The location of the notch was marked on the polished and etched weld specimens close to the fusion boundary such that the notch tip samples CGHAZ area. For each of the HAZ conditions, at least ten specimens were tested. Presented in Table IV are the results from these tests.

Single edge notch bend geometry was chosen for fracture toughness testing of weld HAZ specimen conditions. The specimens were prepared as per BS 5762. The HAZ specimens were surface ground and finished to 2μm on the notch side and its opposite face. In three point bend (TPB) specimens for fracture toughness tests, 4mm deep notch was machined close to the fusion boundary in the CGHAZ in a similar way as CVN impact test specimens. All the fracture toughness specimens were fatigue precracked to an a/W ratio of $\cong$ 0.5 where a is the total crack length and W is the specimen width. The loading of the specimens was continued till an appreciable load drop was detected during the test. The on-line digital P(load) vs.CMOD (crack mouth opening displacement) data collected through a PC was converted to CTOD as per BS 5762 standard employing the following equation :

$$\text{CTOD} = \delta = \frac{K^2\,(1-V^2)}{2\sigma_y\,E} + \frac{V_p}{1 + \dfrac{a + z}{r\,(W - a)}} \qquad .....(1)$$

where, K is the stress intensity factor, v is the Poisson's ratio; E is the Young's modulus; a is the crack length; W is the specimen width; z is the thickness of the knife edge; V_p is the plastic opening of the COD gauge, r is a rotational factor taken as 0.45. It may be noted that wherever fracture toughness has been mentioned in this investigation, it refers to CTOD value obtained from eqn. (1). At least 4 to 6 specimens were tested for each of the welded conditions for the evaluation of HAZ toughness.

Table III : Tensile properties of HAZ obtained in different welding processes.

Type of weld	No. of specimens tested	YS 0.2%, MPa	UTS, MPa	% Elongation
MMAW	2	424, 399	569, 546	27.6, 26.8
SAW	2	399, 375	508, 521	31.0, 32.2
GMAW	2	418, 406	536, 554	25.6, 26.0
Base material	2	424, 436	620, 611	30.0, 31.4

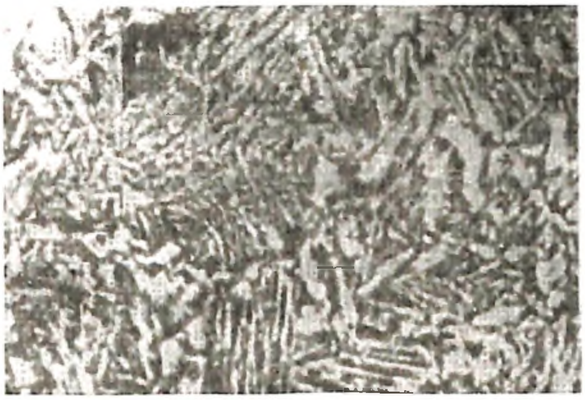
The fracture surfaces were ultrasonically cleaned and then examined under a scanning electron microscope. The scan was limited to the immediate vicinity of the fatigue crack tip in the TPB specimens or notch tip in the CVN specimens, where the crack initiation is expected to occur. Significant fracture features were recorded at a magnification of about 500x.

RESULTS AND DISCUSSION

Tensile Properties : The weld HAZ tensile samples showed yield strength in the range of 380 to 460 MPa (Table III) for all the three welding processes and are comparable to the strength of the parent material. Similar values have been reported for submerged arc weld HAZ by Wang et al. [7]. The tensile strength and % elongation measured was also comparable to those of the base material. It appears that the small volume fraction of brittle microstructural regions in the CGHAZ (Table 2) or ICHAZ does not seriously impair the tensile properties. It may be seen from Fig.2 that the CGHAZ in MMAW and SAW showed predominantly ferrite carbide aggregates within the coarse prior austenite grains close to the fusion boundary. Additionally, the HAZ, which was measured to be about 2.8-4.2mm and would constitute only part of the gauge length of the tensile test specimens used in the present investigation, would be encompassed either by lower strength base material or weld metal. It is generally understood that low strength microstructural regions would yield first instead of the high strength brittle microstructural regions of HAZ because of the movement of the plastic hinge from harder HAZ into surrounding ductile regions [8, 9].

CVN Impact toughness : The assessment of impact toughness has been restricted to CGHAZ region, which showed brittle microstructures (Fig.2) and higher hardness. In the case of manual metal arc welding, the lowest impact energy measured was about 65J among the several samples tested. Microscopic examination of such a sample showed that the fracture region sampled was predominantly CGHAZ. Typical SEM fractographs of the specimens close to the notch tip region, which showed lowest toughness, are shown in Fig.3. The material exhibited transgranular quasi-cleavage fracture in this region. The CGHAZ in MMAW has shown an average micro hardness of about 296HV which was largely due to ferrite and ferrite carbide aggregates.

Among the HAZ specimens in submerged arc weld tested for CVN impact toughness, the lowest value obtained was about 57J and the maximum 92J. The examination of fractured surfaces of the sample having the lowest toughness (57J), revealed transgranular quasi-cleavage failure. This is evident from the large cleavage facets as shown in Fig. 3b. The micro hardness of this region was found to be 287Hv, which represents a typical value for ferrite carbide aggregates.

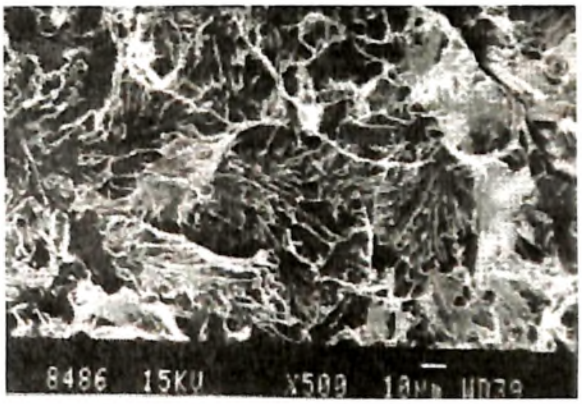


a) MMAW CGHAZ (500x),
0.97mm from fusion boundary (FB)

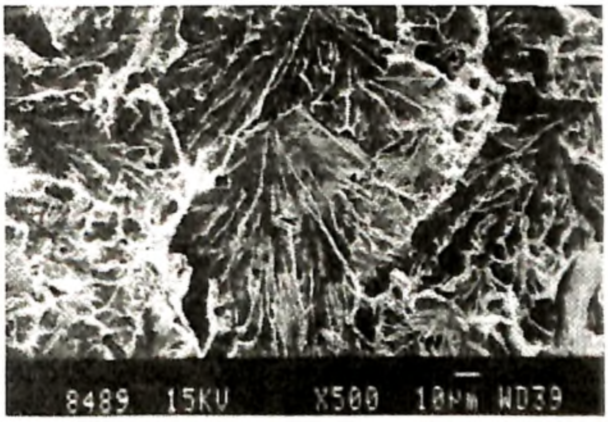
b) SAW CGHAZ (200x) ,1.58mm from FB

c) GMAW CGHAZ (500x), 0.91mm from FB

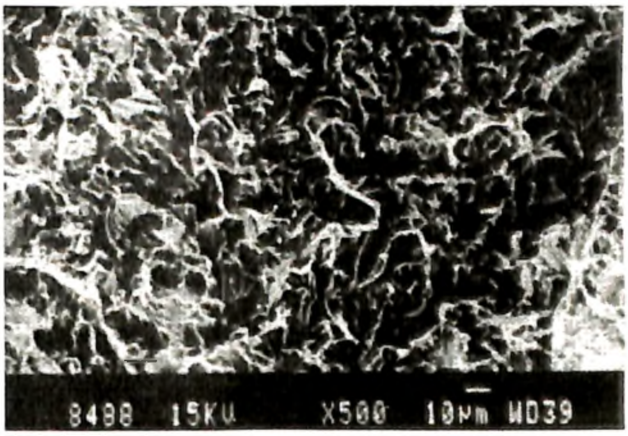
Fig. 2 Representative microstructures of CGHAZ in different welds



a) MMAW CGHAZ (~0.5mm from FB)



b) SAW CGHAZ (~0.5mm from FB)



c) GMAW CG-FGHAZ transition region
(~1.1mm from FB)

Fig.3 Typical SEM fractographs of CVN impact specimens that showed lowest toughness.

The lowest notch toughness of HAZ in gas metal arc weld was found to be 52J in comparison to toughness of 84J for the base material. The microscopic examination of fractured surfaces, close to the notch, showed distinct pockets of bright crystalline areas amongst regions having dimples indicating presence of brittle phases. A typical fractograph of the sample (which measured 52J) showing the brittle fracture area is presented in Fig. 3c. From the size of fractured grains it appears that the specimen has sampled transition region between CGHAZ and FGHAZ. In this region the microstructure was found to consist of a mixture of martensite, ferrite and ferrite carbide aggregates. The micro hardness measured was found to be 275H.

The uncertainty associated with the location of notch [10, 11] has resulted in a large scatter (Table IV) in the estimation of the notch toughness of CGHAZ. However, the data provides an indication of poor impact toughness associated with brittle microstructural conditions and coarser prior austenite grain sizes in the HAZ as can be seen from Table 4 where low toughness is recorded in some of the samples tested. The HAZ from GMAW welding process showed lower toughness compared to MMAW and SAW because of the presence of higher volume fraction of martensitic microstructure.

Fracture toughness : It is envisaged that a finite root radius ($\approx$0.25mm) of the V notch in the CVN impact specimen entails several heterogeneous grains of the microstructure. In addition, the value represents the total energy required for both the crack initiation and further growth of the crack. In a CVN test it is difficult to distinguish between the two and the toughness value is likely to represent an average value for a heterogeneous microstructure. However, in fracture mechanics tests,a sharp fatigue precrack narrows down the heterogeneity of the microstructures. Further, such tests would reveal the crack initiation toughness/critical fracture toughness, separated from the crack growth toughness. Most of the tested specimens exhibited a smooth and continuously increasing load with increasing displacement up to a certain maximum load followed by steadily decreasing load as shown in Fig. 4a. A few specimens showed pop-ins on account of sudden load drop because of small brittle crack extensions, on the rising part of the load curve (Fig. 4b). As suggested by the standards [12, 13], the critical CTOD δ_c was calculated at the first load maxima in case of the former and at the pop-in loads in case of the latter. The results of the CTOD tests are presented in Table V.

Barring the cases of pop-ins, both MMAW and SAW showed relatively same range of critical $CTOD_c$, δ_c of 0.18 to 0.28mm. These are slightly higher than those of the base material (δ_c= 0.188mm). Kocak et al. [14] and Toyoda et al. [15] have

Table IV : Room temperature CVN impact toughness of HAZ obtained in different welding conditions

Type of weld	No. of specimens tested	Impact toughness, J
MMAW	10	88, 85, 83, 83, 74, 72, 71, 70, 66, 65
SAW	11	92, 84, 84, 81, 73, 71, 70, 70, 58, 57, 57
GMAW	11	81, 76, 72, 70, 69, 66, 65, 58, 55, 55, 52
Base material	5	82, 84, 81, 86, 87

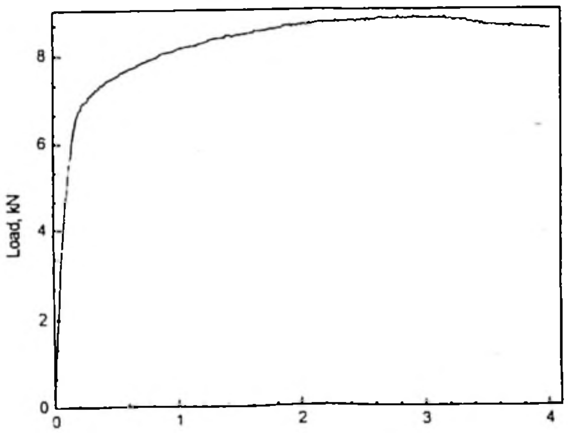


Fig. 4a Record of load-CMOD in case of MMAW HAZ specimen (~ 1mm from fusion boundary).

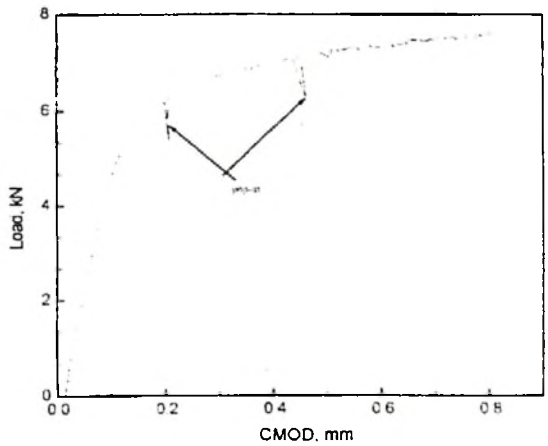


Fig. 4b The load-CMOD plot showing pop-in in case of HAZ of SA weld specimen (~ 0.5mm from fusion boundary).

attributed this apparent increase in the fracture toughness to ductile tearing between the crack tip and the HAZ close to the fusion boundary, forcing the crack to deviate into the softer microstructural regions such as FGHAZ or the weld metal. Thus, the crack tip experiences a mixed mode of opening (tensile) and shear loading enhancing the apparent load bearing capacity of the crack tip. A typical SEM photograph depicting the crack deviation observed in most of the specimens tested for HAZ toughness is shown in Fig. 5. The fracture surface at the deviated crack tip (Fig. 6a) showed dimple rupture confirming the observations. On the other hand, the low fracture toughness associated with pop-ins observed, arises out of small brittle crack extensions accompanied by a decrease in the applied force due to the presence of brittle microstructural regions ahead of the crack tip as has been reported by several investigators [7, 15]. Both MMAW and SAW have shown presence of ferrite side plate microstructure, which possesses lower toughness. The micro hardness survey also showed higher hardness in the CGHAZ (~290H_V) confirming these observations.

Table V : Results of room temperature CTOD fracture toughness tests on HAZ obtained in different welding conditions.

Type of weld	No. of specimens tested	Critical CTOD, δ_c, mm
MMAW	7	0.0463+, 0.101+, 0.177, 0.254, 0.285, 0.271, 0.248
SAW	6	0.090+, 0.282, 0.291, 0.226, 0.198, 0.272,
GMAW	7	0.026+, 0.118, 0.167, 0.194, 0.188, 0.156, 0.173
Base material	2	0.186, 0.190

(+): indicates pop-in

a) End of fatigue crack tip in CGHAZ

b) Crack deviation into weld metal

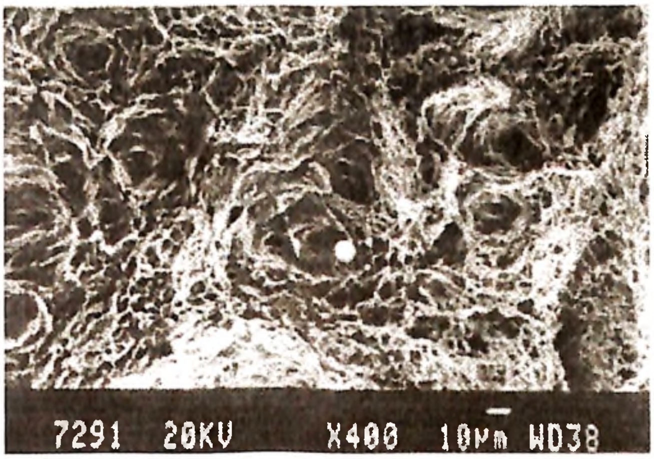
c) Microstructure at the deviated crack tip at the end of CTOD test

Fig. 5 : Typical SEM photomicrographs of CTOD test specimens showing crack deviation into weld metal

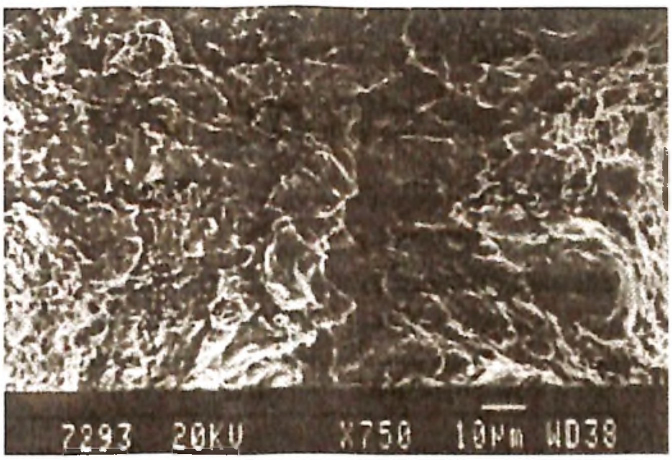
The CGHAZ samples in GMAW, on the other hand, have shown comparatively lower toughness (in the range of 0.12 to 0.19mm) than those of either MMAW or SAW. The crack deviation into the softer regions as well as pop-in behaviour was also observed as in the cases of MMAW and SAW. An examination of fracture surfaces revealed quasi-cleavage failure in the CGHAZ of GMAW. These are presented in Fig. 6b. Low toughness of these regions may be attributed to the presence of predominantly martensitic phase as is evident in Table II.

It may be observed from Table 5 that there are two types of HAZ toughness values, one that is associated with pop-in behaviour and the other where crack deviation has been encountered. From this data a representative fracture toughness value, for the CGHAZ condition tested, has to be arrived. The document PD6493 [3] recommends a minimum of 3 to 5 fracture toughness tests for level 1 assessment of welded joints and the specimens should result in similar mode of failure - all showing either brittle fracture, or all showing ductile tearing up to maximum load. In addition, it recommends cautious approach to the assessment when the representative lowest value so chosen is less than 50% of the average or the maximum value is more than twice the average of the three test results. It also emphasises that the data representing HAZ toughness should ensure that crack tip is in the same microstructure. Other criteria available in the literature [16, 17] propose sampling of a certain minimum percentage of the desired microstructural region by the crack during monotonic loading. These criteria are limited either to the pop-in situations or to the specimens showing extensive local brittle zone phenomenon.

All these criteria necessitate testing of a large number of samples to arrive at a valid fracture toughness data that represents a particular region of HAZ. Pre and post metallographic examination of the specimens is a must. In practice testing of large number of specimens is both time consuming and expensive and sometimes it is impractical because of the non-availability of the specimen material. In addition, there exists a great degree of uncertainty associated with the recorded test data for the occurrence of similar type of failure during testing. This is largely governed by the orientation of the brittle phase or defect ahead of the growing crack tip to the



a) MMAW



b) GMAW

Fig. 6 Typical fractographs of weld HAZ composite CTOD specimens

applied load. This would create an ambiguity with respect to the selection of representative data for the HAZ toughness from the point of view of service specification. There is an immense need for a simpler and easy to implement criterion for validating the test data and to formulate specimen sampling procedures for obtaining optimum fracture toughness value. Testing of HAZ microstructural condition through simulation is one such technique for obtaining conservative property data at the cost of disregarding the effect of microstructural gradient present in the weld HAZ. In practice,a representative HAZ toughness of desired microstructural region would possibly be a weighted index of the toughness comprising of adjacent microstructural conditions as well.

CONCLUSIONS

A critical examination of the fracture toughness data along with the microstructural details of the HAZ region brings out necessity of considering HAZ specimens as composite specimens. Among the three weld heat affected zones, GMAW showed lower toughness. This may be due to faster cooling rates experienced by the material in the heat affected zone thus forming higher volume fraction of martensitic phase. In the absence of any standard procedures for testing weld HAZ and the variations that could arise out of inaccurate location of the crack tip, it is necessary to test the material under wide range of microstructural conditions. There exists a great need of evolving a procedure to obtain toughness index for the overall weld-HAZ microstructures considering their inherent heterogeneity.

REFERENCES

1. Welding Hand Book, 8th Edition, Welding Technology, 1, 1991, Ch.5.
2. Rowland Harman (Ed.), Hand Book for Welding Design, 1, The Institute of Welding, 1956, Ch.6.
3. Guidance on Methods for Assessing Acceptability of Flaws in Fusion Welded Structures, Published Document, PD:6493, BSI, 1991.
4. IIW Document SST-1157-90, Guidance on Assessment of the Fitness

for Purpose of Welded Structures, 1990.

5. Lancaster J., Handbook of Structural Welding, Abington Publishing, Cambridge, 1992, Ch.6.

6. Seshu Kumar A., Ph.D Thesis, Indian Institute of Technology, December 1999.

7. Wang G.R., North T.H. and Lewis K.G. Welding Journal, 1990, 69, p.145s.

8. Dolby R.E., Metal Construction, 1972, 4, p.59.

9. Daynes R. M., Proceedings of the International Conference on Weld Failures, London, England, 21-24 Nov. 1988, Welding Institute, p.133.

10. B4 Committee on Mechanical Testing of Welds, Welding Journal, 1981, 60, p.37.

11. Prasanna Kumar S, Ramachandran E.G. and Ruge J, Metal Construction, 1983, 15, p.142.

12. BS 5762: 1979, Methods for Crack Opening Displacement Testing, The British Standards Institution.

13. ASTM E 1290-93: Standard Test Method for Crack Tip Opening Displacement Fracture Toughness Measurement, Annual book of ASTM Standards,1998, 3.01

14. Kocak M., Schwalbe K.H., Chen L. and Gnirss G., Proceedings of the International Conference on Weld Failures, London, 21-24 Nov., 1988, Welding Institute, p.163.

15. Tayoda M and Satoh K., Welding in the world, 1984, 22, p.76.

16. Kohler G., Whitfield R. and Chipperfield C., Theoretical and Applied Fracture Mechanics, 1986, 6, p.39.

17. Fairchild D.P., Theisen J.D. and Royer C.P., Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering, Houston, Welding Institute, London, 1988, 3, p.247.

SMART NDT ACADEMY

Developing NDT trainees to enhance personnel skills as per ASNT/ISNT norms.
Certification courses on Welding for Engineers/Welders.
Training shall be conducted by well-qualified & experienced faculty.

COURSE SCHEDULE 2001 :

Method	Period (April 2001 - Jan 2001)		
LPT – II	Apr 27 – Apr 30	July 30 – Aug 1	Nov 19 – Nov 21
MT – II	May 2 – May 5	Aug 2 – Aug 5	Nov 22 – Nov 25
RT – II	May 7 – May 16	Aug 6 – Aug 16	Nov 26 – Dec 5
UT – I	May 17 – May 23	Aug 17 – Aug 23	Dec 6 – Dec 12
UT II	May 24 – June 2	Aug 24 – Sep 2	Dec 13 – Dec 22
Interpretation of RT*	June 3 – June 7	Sept 3 – Sept 7	Dec 23 – Dec 27
Welding Inspector*	June 8 – June 14	Sept 8 – Sept 14	Dec 28 – Jan 3

* Tentative Schedule

We also conduct on Site Classroom courses for Engineers/Managers.

Contact :

OFFSHORE TESTING & INSPECTION SERVICES (I) PVT. LTD.
W-147, MIDC Pawane, Thane Belapur Road, Navi Mumbai 400 703, India.
Tel : +91 22 7681946 / 7670874 / 7901229 Fax : +91 22 7633982 / 5561249
Email : otislab.vsnl.net